Yaw Motion Analysis Of Single-Trailer Truck Using Yaw Amplification Factor (YAF)

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***Abstract*— This study investigates a yaw motion analysis of single trailer-truck using yaw amplification factor (YAF) approach. Unwanted yaw motion in single-trailer truck can cause instability of the truck vehicle and resulting road accident such as knife-jacking. This study focused on applying brake pressure to predict the jack-knife accident. The trailer truck was tested at 100 km/h while applying various brake pressures at 0.5 MPa, 1.0 MPa, 1.5 MPa, 2.0 MPa and 2.5 MPa during single lane change and double lane change using TruckSim software. Yaw Amplification Factor (YAF) was used to analyse the yaw movement in the single-trailer truck. The indicator of yaw amplification factor to predict jack-knifing which is related to unwanted yaw motion of a truck was implemented in this study to the potential accident analysis. This study showed that jack-knife accident happened when travelling at 100 km/h when applying the brake pressures of 1.5 MPa and 2.5 MPa for single lane change manoeuvre. Similarly, jack-knife accident also happened when travelling at 100 km/h for double lane change manoeuvre with brake pressures of 1.5 MPa, 2.0 MPa and 2.5 MPa. These findings are based on C_m indicator to predict jack-knife accident.**

Keywords — single-trailer truck, YAF, jack-knife accident

I. INTRODUCTION

In general, single-trailer trucks have various advantages in transportation, including the capacity to send a large and heavy load with a flexible delivery cost, as well as easy loading and unloading. When it comes to accidents, there must be a specific circumstances that are linked to other vehicles, as well as the driver's own risks that may cause the road accident [1]. To increase safety, new trucks must include anti-lock brakes, electronic stability control, forward collision warning, and automatic emergency braking. Adaptive cruise control, intelligent speed adaptation, blind spot information, and curve-speed warning are non-mandatory features that are available for new vehicles [2]. Accidents involving big trucks have serious consequences for road users, and often cause major traffic congestion as well as environmental or infrastructural damage, all of which incur significant financial expenses. Several solutions have been studied to reduce the number of accidents and increase safety in some programs that deal with the idea and activity of Intelligent Transportation Systems (US NAHSC program, California PATH programme, Japan's AHSRA, European programmes: ADASE, REPONSE, and CHAUFEUR-driven, French PREDIT and ARCOS programmes, etc.) [3]. The most significant difficulty with a large truck is its manoeuvrability, especially while going at high speeds, it can produce unwanted reactions such as severe yaw disturbance, which can result in jack-knifing, trailer oscillation, and trailer swing. Jack-knifing of semi-trailer articulated vehicles are situations that requires a well-trained driver. Untrained drivers are unable to regulate such conditions [4], which may result in the vehicle losing its stability, resulting in the loss of life and property.

Steering controls and differential brake controls are the most common and have been investigated to increase stability for truck semi-trailer systems, according to earlier research. The most important step in developing any controller is to simulate it. It's because the controller's characteristics are investigated for optimal conditions, and settings are fine-tuned to ensure the controller's best performance. The optimal rear wheel steering controller was found to stabilise the car utilising two replies feedback states of the vehicle, such as hitch angle and hitch angle rate, yaw rate, and slip angle, in the previous research [5]. Jack-knifing is characterised as a lack of stability in the articulated system's yaw motion. Jack-knifing happens for a variety of reasons, including when the tractor's rear wheels are obstructed, when the vehicle rapidly applies the brakes in turn, or when the road is slippery (low adherence). This occurs more frequently when the truck is empty or has a poor useable charge distribution [3]. The side pressures generated by control in a turn, as well as the condition of the road, are essential elements in jack-knifing. In theory, jack-knifing occurs when the tractor is positioned at an angle of at least 90 degrees to the semi-trailer [6]. Because of the force exerted by the trailer, the tractor's driving wheels lose their adhesion and become involved to the right or left. Fig. 1 shows the jack-knifing situation of heavy vehicle.

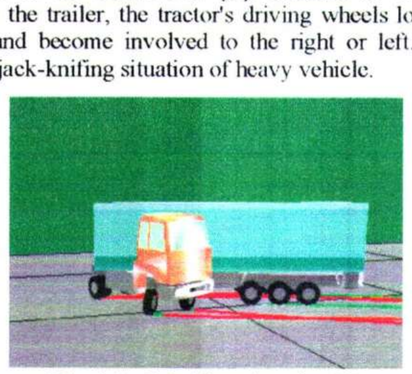

Fig. 1. Jack-knifing situation [3].

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II. JACK-KNIFING DETECTION ALGORITHM

Fig. 2 shows the articulated vehicle in the reference of (O, X_E, Y_E) with the coordinates of points P_1 and P_2 that will be used to determine the jack-knifing situation based on cross product as follows.

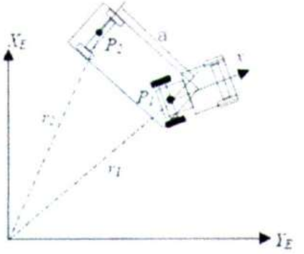

Fig. 2. Articulated vehicle position.

$$C_m = \frac{\dot{x} - y\dot{\psi}}{\dot{y} + x\dot{\psi}} = tan(\psi_f) \quad (1)$$

This equation represents the criterion of truck jack-knifing. To be able to identify and forecast a jack-knifing situation, it is required to establish zones of stability for yaw angle. This zone is defined as ψ_f, articulation angle. It fluctuates between [-85°, +85°] that was showed as $C_m = tan(\psi_f)$. It denotes the zone of stability in a jack-knifing incident.

$$tan(-85) < C_m = \frac{\dot{x} - y\dot{\psi}}{\dot{y} + x\dot{\psi}} < tan(85) \quad (2)$$

The approach for predicting accident risks (jack-knifing) is based on the development of the criteria, which is determined about the predicted state. For each time path, the tangent line of the evolution curve is computed. Thus, the length between the present time and the moment corresponding to the intersecting axis between the tangent line and the threshold value is determined at each point of the curve that determines the risk level as shown in Fig. 3.

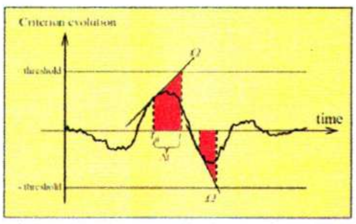

Fig. 3. Risk criterion prediction - time left before the accident (TLBA) [7].

The risk criterion is based on prediction time duration that determined according to:

$$\Omega = C'_m(t_0)(t - t_0) + C_m(t_0) = C'_m(t_0)\Delta t + C_m(t_0)$$

$$\Omega = threshold \quad (3)$$

So, this gives threshold, $\Omega = f'(x_0)\Delta t + f(x_0), then$

$$\Delta t = \frac{threshold - C_m(t_0)}{C'_m(t_0)} \quad (4)$$

III. TRUCKSIM SOFTWARE FOR MOTION ANALYSIS

TruckSim software is used to provide data information on trailer truck during single lane change (SLC) and double lane change (DLC) travelling at 80 km/h. This data will be analysed to determine its yaw motions that affect the yaw stability. Fig. 4 shows main page of TruckSim 2016 software. The development of TruckSim software is based on real world validation [8].

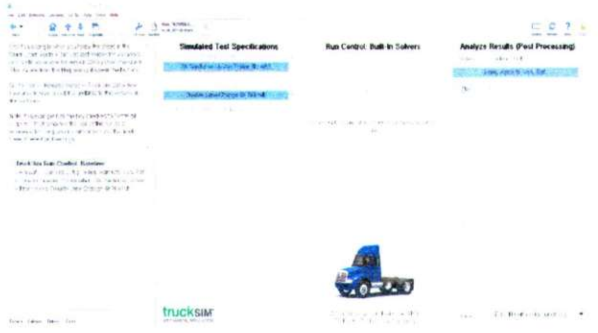

Fig. 4. Main page of TruckSim software.

Main page TruckSim 2016 software consists of three steps to run simulation. First step is simulated test specifications where vehicle configuration will be chosen. The vehicle configuration chosen is 2 axle truck with 1 axle van trailer indicates 3 axle trailer-truck. Next, procedure to run the simulation is chosen where SLC and DLC are chosen. Second step is run the simulation, in this step the simulation will run based on test specifications set on first step. Last step is analysing the results which is post-processing. After running the simulation, the results can be obtained at this step where data can be taken for further analysis. Fig. 5 shows procedure to run TruckSim 2016 software and data plotting MATLAB Simulink.

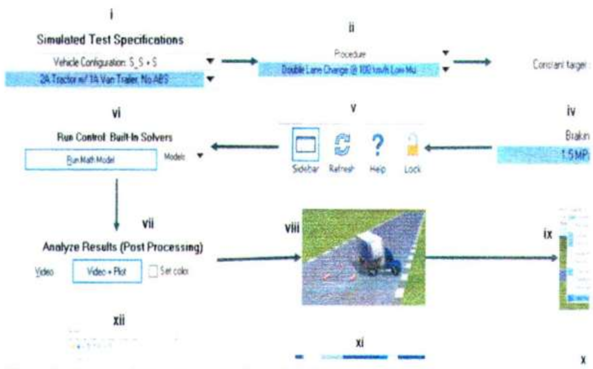

Fig. 5. Procedure to run TruckSim Software and plot data in MATLAB Simulink.

Fig. 5 has twelve steps to obtain the simulation data as presented. First step is choosing 3 axle trailer-truck to be analysed. Next step is determining the procedure that will be used which are SLC and DLC. Then, speed of trailer-truck is set to be 100 km/h for high speed. After that, braking brake control is determined with various braking pressure at 0.5 MPa, 1.0 MPa, 1.5 MPa, 2.0 MPa and 2.5 MPa. The page is refreshed to make sure the software shows data set. Math model of the configuration set will be run then the results of the simulation can be obtained by click "Video+Plot". The simulation result is shown and responses of yaw rate and yaw angle can be obtained from data manager and next transferred to MATLAB to get the graph.

IV. Simulation of Jack-Knife Accident for Single and Double Lane Change Tests

The results and analysis of this study are described in this section. The truck is analysed at speed 100 km/h. There are two maneuvering tests conducted in this study namely single lane change (SLC) and double lane change (DLC) while applying various brake pressures which are 0.5 MPa, 1.0 MPa, 1.5 MPa, 2.0 MPa and 2.5 MPa. The simulation results of yaw rate, yaw angle and development of C_m responses indicate the influence of road courses and brake pressure jack-knife accidents. The response of yaw rate is used to examine the potential of jack-knife accident, while yaw angle response will be analyzing the trend of jack-knife accident during lane change manoeuvres. Indicator of C_m is used as in [7] where threshold value which will indicate the jack-knifing accident. Threshold value is used to predict the jack-knifing accident when the response of Cm approaching the threshold value. For the first step of simulation, yaw angle response is analysed by identifying the threshold value. The response of SLC of the 3-axle trailer truck is shown in Fig. 6.

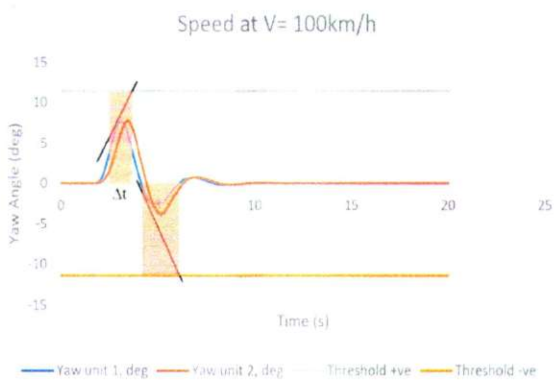

Fig. 6. Graph for SLC at 100 km/h.

In order to find the indication between the tangent line on graph, two points which are upper and lower are determined and the tangential line slope is calculated then plotted on the graph. Here, there are two tangential lines can be found in the graph which are upper tangent line and lower tangent line as tabulated in Tables 1 and 2.

TABLE 1 POINT TO FIND UPPER SLOPE SLC AT 100 KM/H

Point x	$x = 2.78$	$x_0 = 2.40$	$x_1 = 3.63$
Point y	$y = 6.47$	$y_0 = 4.95$	$y_1 = 11.43$

From the point values, slope of the tangent line for SLC at 100 km/h is calculated

$$Slope = \frac{11.43-4.95}{3.63-2.40} = 5.27$$

So, the slope of the upper tangent line at speed at 100 km/h is 5.27, followed by lower slope -4.82.

TABLE 2 POINT TO FIND LOWER SLOPE SLC AT 100 KM/H

Point x	$x = 4.63$	$x_0 = 4.03$	$x_1 = 6.25$
Point y	$y = -1.81$	$y_0 = -0.71$	$y_1 = -11.43$

$$Slope = \frac{-11.43-(-0.71)}{6.25-4.03} = -4.82$$

Fig. 7 shows yaw rate response with comparison between five different brake pressures for single lane change at 100 km/h. As can be seen in Fig. 7, when brake pressure applied at 1.5 MPa when travelling at speed 100 km/h, yaw rate for this condition rapidly increases after 11 seconds which the truck losing its control as in [9] and resulting jack-knife accident during lane change manoeuvres. Yaw rate for brake pressure 2.5 MPa and 2.0 MPa are lower compared to brake pressure 1.5 MPa but it occurred after 13 seconds which causing instability to truck. For other brake pressures applied which are 0.5 MPa and 1.0 MPa, the yaw rate response for this case is the lowest compared to others due to small brake pressure applied on wheel did not affect the yaw stability of the truck which the truck will stop moving in stable condition.

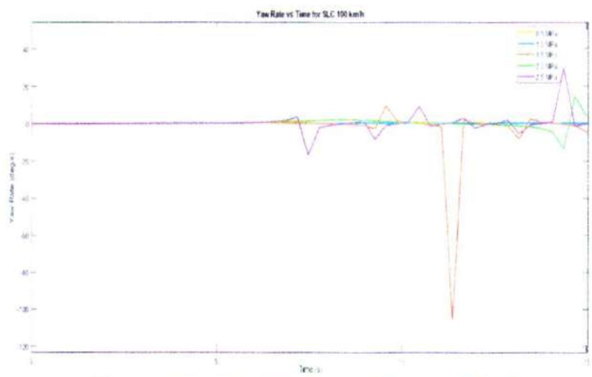

Fig. 7. Yaw rate response for SLC 100 km/h.

Fig. 8 shows yaw angle response and Fig. 9 shows Cm indicator for jack-knife accident for single lane change at speed 100 km/h. It can be seen that there are two conditions that causing the truck jack-knife which are brake pressures applied at 1.5 MPa and 2.5 MPa. This jack-knife occurs when Cm value of the truck exceeds threshold value at 11.43 and -11.43 as in [3]. The earliest jack-knifing accident happen after 7 seconds for brake pressure at 2.5 MPa where its Cm value exceeds the threshold value then continuing to jack-knife. As can be seen in Fig. 8, truck yaw angle is continuing to jack-knife to the highest angle at 9.55 seconds where its yaw angle is at 70.09 deg. This is due to when brake applied after the truck changing the lane, lateral acceleration of the truck of the truck when changing the lane still affect the yaw movement and causing the truck to lose its control as in [9]. Load of the truck also affect the yaw movement of the truck when travelling at high speed during lane change when applying the brake pressure as in [10].

There is no jack-knifing occurred when brake pressure 0.5 MPa and 1.0 MPa applied as C_m value of the truck did not touch threshold line during lane change, resulting the truck stop with no accident happened. After 10 seconds, the C_m value and yaw angle is continuing straight indicates the truck is completely stop.

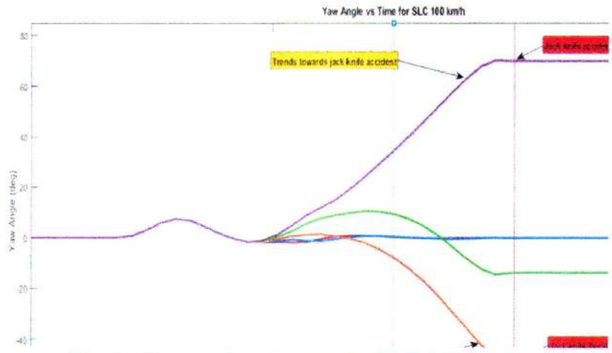

Fig. 8. Yaw angle response for SLC 100 km/h.

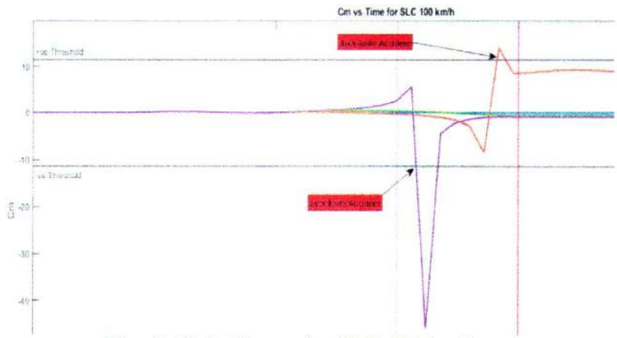

Fig. 9. C_m indicator for SLC 100 km/h.

Next assessment is double lane change (DLC) at speed 100 km/h. There are two lines need to be identified namely upper and lower tangent lines as illustrated in Fig. 10. Upper tangent line is calculated from the data in Table 3.

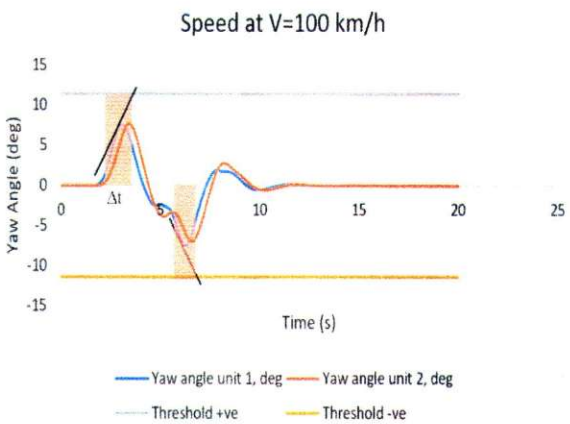

Fig. 10. Graph for DLC at 100 km/h

TABLE 3 Point to find upper slope DLC at 100 km/h

Point x	$x = 3.1$	$x_0 = 2.23$	$x_1 = 3.40$
Point y	$y = 6.46$	$y_0 = 3.01$	$y_1 = 11.43$

$$Slope = \frac{11.43-3.01}{3.40 \quad 2.23} = 7.20$$

As the result, the slope for upper tangent line at 100 km/h of double lane change is 7.20. Meanwhile lower tangent line is -5.71 based on calculation in Table 4.

TABLE 4 Point to find lower slope DLC at 100 km/h

Point x	$x=6.4$	$x_0 = 5.80$	$x_1 = 6.95$
Point y	$y = -6.49$	$y_0 = -4.86$	$y_1 = -11.43$

$$Slope = \frac{-11.43-(-4.86)}{6.95-5.80} = -5.71$$

Fig. 11 shows the yaw rate response between five different brake pressures applied for double lane change at 100 km/h.

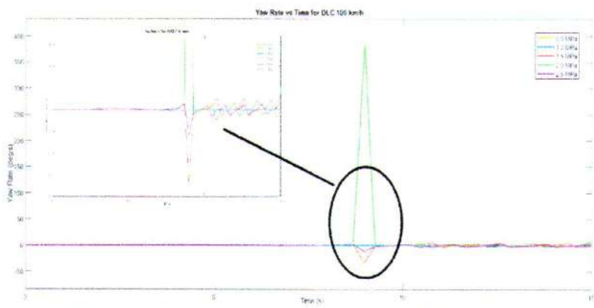

Fig. 11. Yaw rate response for DLC 100 km/h.

As can be seen on yaw rate response for double lane change at speed 100 km/h, yaw rate at brake pressure 2.0 MPa showed it is rapidly increasing after 8 seconds to the highest yaw rate above 300 deg/s as shown in Fig. 11, then rapidly decreased. At brake pressure 1.5 MPa, yaw rate rapidly decreasing below -30 deg/s indicates that truck losing its stability when applying brake. At brake pressure 2.5 MPa, yaw rate rapidly decreases to below -10 deg/s meaning yaw stability of the truck started to lose. For brake pressure 0.5 MPa and 1.0 MPa, yaw rate of the truck remains stable indicates that the truck in stable condition during lane change. Next, Fig. 12 shows yaw angle response and Fig. 13 shows C_m indicator to predict jack-knife accident for double lane change case at speed 100 km/h.

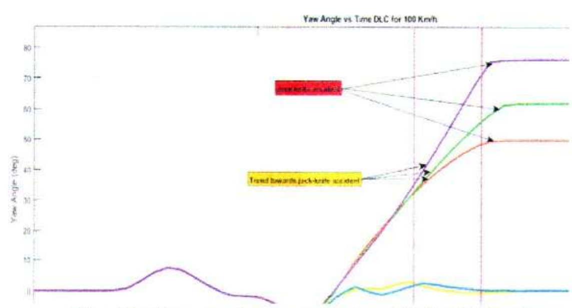

Fig. 12. Yaw angle response for DLC 100 km/h.

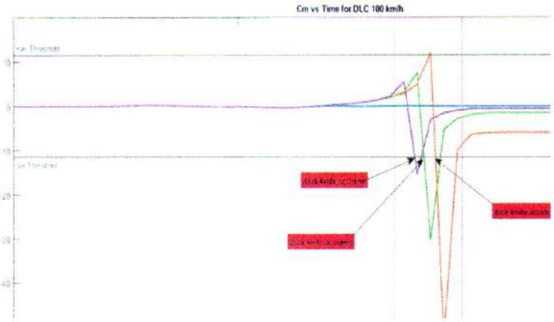

Fig. 13. C_m indicator for DLC 100 km/h.

From Fig. 13, there is three conditions that causing jack-knife accident of the truck when brake pressure applied at 1.5 MPa, 2.0 MPa and 2.5 MPa. C_m response exceeds threshold value at 11.43 and -11.43, this indicates that the jack-knife starts to happen. As can be seen on the Fig. 13, three conditions of brake pressure applied have similar jack-knife after 8 seconds where yaw angle above 30 deg. However, the earliest jack-knife condition starts at 7 second when brake pressure applied at 2.5 MPa. Next jack-knife condition occurred after 7.5 seconds at brake pressure 2.0 MPa followed by 1.5 MPa which jack-knife occur after 8 second. These accidents of jack-knife continuing happen until reach the highest yaw angle and stop after reaching max yaw angle for each condition meaning that the truck losing yaw stability as in [9]. While jack-knife accident did not happen at brake pressure 0.5 MPa and 1.0 MPa because the C_m response did not exceed threshold value indicates that the yaw of the truck still can be controlled when applying these brake pressure. But higher brake pressure applied on the truck will cause yaw angle became higher that causing jack-knife accident as in [10]. This is because lateral acceleration of the truck is higher at high speed when brake is applied causing the truck to glide from the road which affect yaw movement then causing the accident of the truck when changing lane. The highest yaw angle is 76.17 deg at 2.5 MPa then 61.77 deg at 2 MPa followed by 49.80 deg at 1.5 MPa. From the Fig. 12, the yaw angle is continuing straight after 10 seconds indicates the truck is completely stop. C_m response indicates that at high speed with sudden braking at higher pressure led to jack-knife accident.

V. CONCLUSION

Based on results obtained, jack-knife accident of truck is influenced by various brake pressures applied with different speeds of truck. This simulation was performed on normal condition of road without taking any environment factors such as wet road, bumpy road and inclined road. The results indicated that jack-knifing of the truck occur while applying highest brake pressure during changing lane. C_m was used an indicator to predict jack-knifing accident to alert the driver to prevent an accident based on the yaw motions. The result obtained may differ from real condition thus further study needed to be done by considering the external disturbances.

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